The 4th Dimension: The Need for High Resolution Imaging Spectroscopy

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There is an important gap in the current "Living with a Star" mission plan. While multi-thermal imaging is well addressed, and accepted as crucial to understanding the dynamic behavior of the Sun, time-resolved spectroscopic imaging has been largely omitted. Simultaneous spectroscopy and multi-thermal imaging at high time cadence is essential to removing interpretational ambiguities and bringing scientific closure to the high resolution dynamic motions seen with SOHO and TRACE. The EUV Solar Spectroscopic Explorer (ESSEX) addresses these concerns, provides greatly improved understanding of the Sun and its influence on the Earth, and augments the "Living with a Star" theme.

Introduction

Complex, evolving systems of ionized plasma and magnetic field are ubiquitous throughout astrophysics and are a quintessential part of space physics, from the solar atmosphere to the solar-terrestrial environment. However, understanding of these complex systems has remained elusive. Fundamental questions remain about the detailed dynamics of both large and small scale structure in the solar atmosphere.

What is the physical nature of the rapidly varying cascade of energy from the solar interior to the solar corona and Earth's space environment?

What is the mechanism whereby this energy is transformed to coronal heat and excitation?

What are the conditions that allow metastable structures to accumulate and store energy, and what are the triggers that cause the release of CMEs and flares?

These questions are directly related to the "Living with a Star" theme, as well as to two of the primary Quests in NASA's SEC program. Only simultaneous spectroscopy and multi-thermal imaging together can provide the new measurements necessary to *remove interpretational ambiguities inherent in current imaging missions*.

High resolution imaging spectroscopy is critical to understanding, for example, the early stages of eruption of CMEs as well as the origin and mechanisms of coronal heating. It will benefit not only solar physics and the "Living with a Star" theme, but also fields ranging from astrophysics in general to space weather and laboratory plasma stability.

Magnetic Connections and Reconnections: Energy Transport and Coronal Heating

What is the mechanism whereby magnetic energy is transformed to coronal heat and excitation?

Magnetic reconnection is intimately associated with coronal heating. The chromosphere and "quiet corona" are dominated by rapid, small, stochastic energy releases associated with motion of ephemeral magnetic flux concentrations in the photosphere. Large coronal features such as loops both undergo large-scale reconnection and also exhibit stochastic brightenings that hint at smaller reconnections within their fine structure. Larger-scale reconnection is surmised to be the energy source for events as diverse as solar flares (e.g., Shibata, *et al.* 1995) and coronal bright points (Longcope 1998).

However, the nature of the basic processes of reconnection – energy storage, triggering, and conversion – is still poorly understood. High cadence TRACE image sequences of large reconnective events demonstrate clearly the associated changes in morphology and hint at plasma motions associated with the events; but because of ambiguities between thermal and density changes in the plasma, and between proper motion and successive illumination of visible features, they cannot by themselves capture the nature of the field-matter interaction. Existing and being-built spectrographs such as SOHO/SUMER and Solar-B/EIS lack the simultaneous spatial and temporal resolution to capture the rapid dynamics of coronal reconnections. Without a detailed knowledge of the local energetics and process of reconnection as it occurs in the corona, it is difficult to determine whether there is sufficient free energy available in the small-scale field to power the corona, let alone rule out other mechanisms for coronal heating.

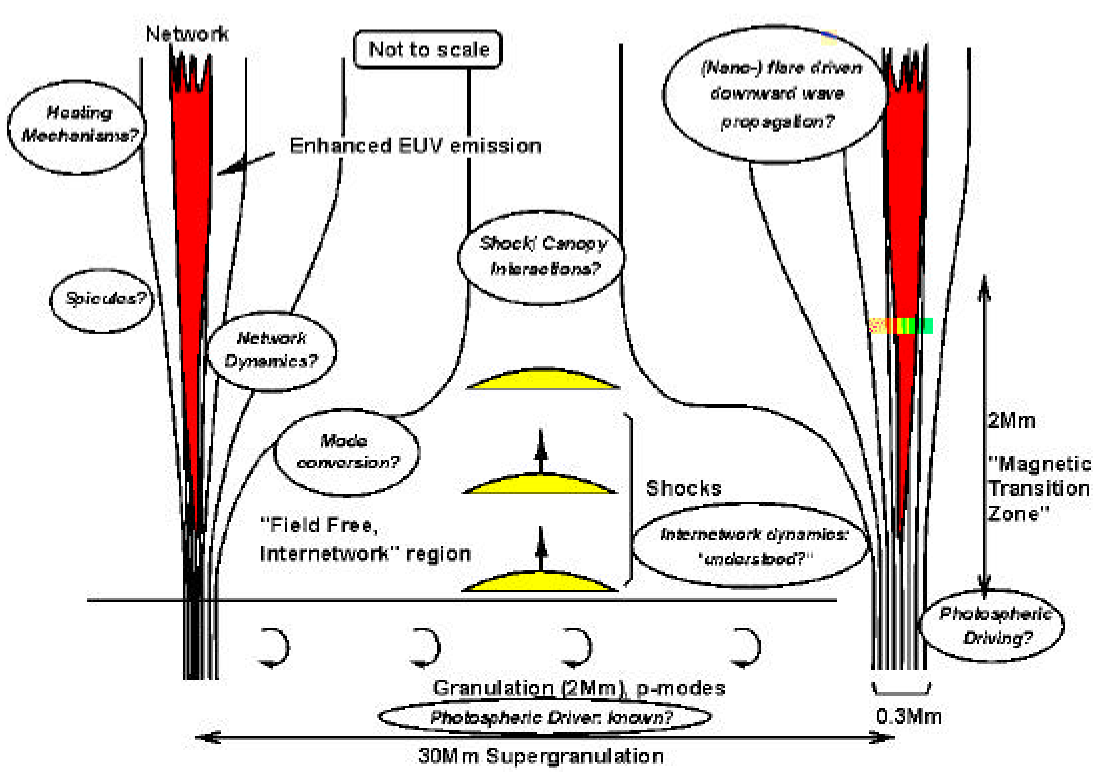

Figure A-4. Cartoon depicting the general morphology of the solar magnetic field through the crucial magnetic transition zone. In the deep photosphere, turbulent plasma flows control the dynamics of the embedded field lines. In the corona, the field entrains the gas and guides its motion. In the intervening "magnetic transition zone," the field dominates where it is strong and gas motions dominate where their amplitudes are large (or the field is weak), thus the influence of one over the other is spatially mixed. Given the relatively large densities, and large amplitudes of unresolved motions in the low chromosphere, energy transfer to the higher layers is magnified.

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Figure 2. Cartoon depicting a solar flare model inspired by Yohkoh and other data (from Shibata, 1997). Maps of temperature and mition are required to distinguish between this and other models.

High Resolution Spectroscopy and "Living with a Star"

A high resolution spectroscopy mission, such as ESSEX, fills a significant gap in the "Living with a Star" theme. Both TRACE and EIT image sequences have emphasized clearly the importance of continuous, synoptic EUV images both for understanding the physics of the solar cycle, and for understanding space weather. They have been fundamental to understanding the nature of coronal structure and CMEs, and their relationship to heliospheric disturbances and geomagnetic activity. *However, high cadence spectroscopic observations are critical to understanding the root causes of these eruptive events.*

The ambiguities in the interpretation of narrowband EUV images and the lack of sufficient cadence and spatial resolution in available spectroscopic data confound studies of individual reconnection events or of wave dynamics in all but a very few cases. To explain fully the physical processes underlying coronal activity, comprehensive, spatially resolved, rapid, simultaneous, co-aligned images and spectral data are required. With a fast optical design, optimized broad-bandwidth detector, and reliable scan mechanisms that are specifically designed for rapid, repetitive motions, it is possible to attain an order-of-magnitude jump in time resolution compared to existing EUV spectrometers.

Limitations of Imaging

Imaging leaves much to be desired as a plasma diagnostic. There are significant ambiguities between bulk motion and successive illumination of adjacent features in any image sequence; between density and temperature variations in sequences from a single narrow spectral band; and between temperature effects and temporal changes in multi-wavelength image sets without strictly simultaneous exposures.

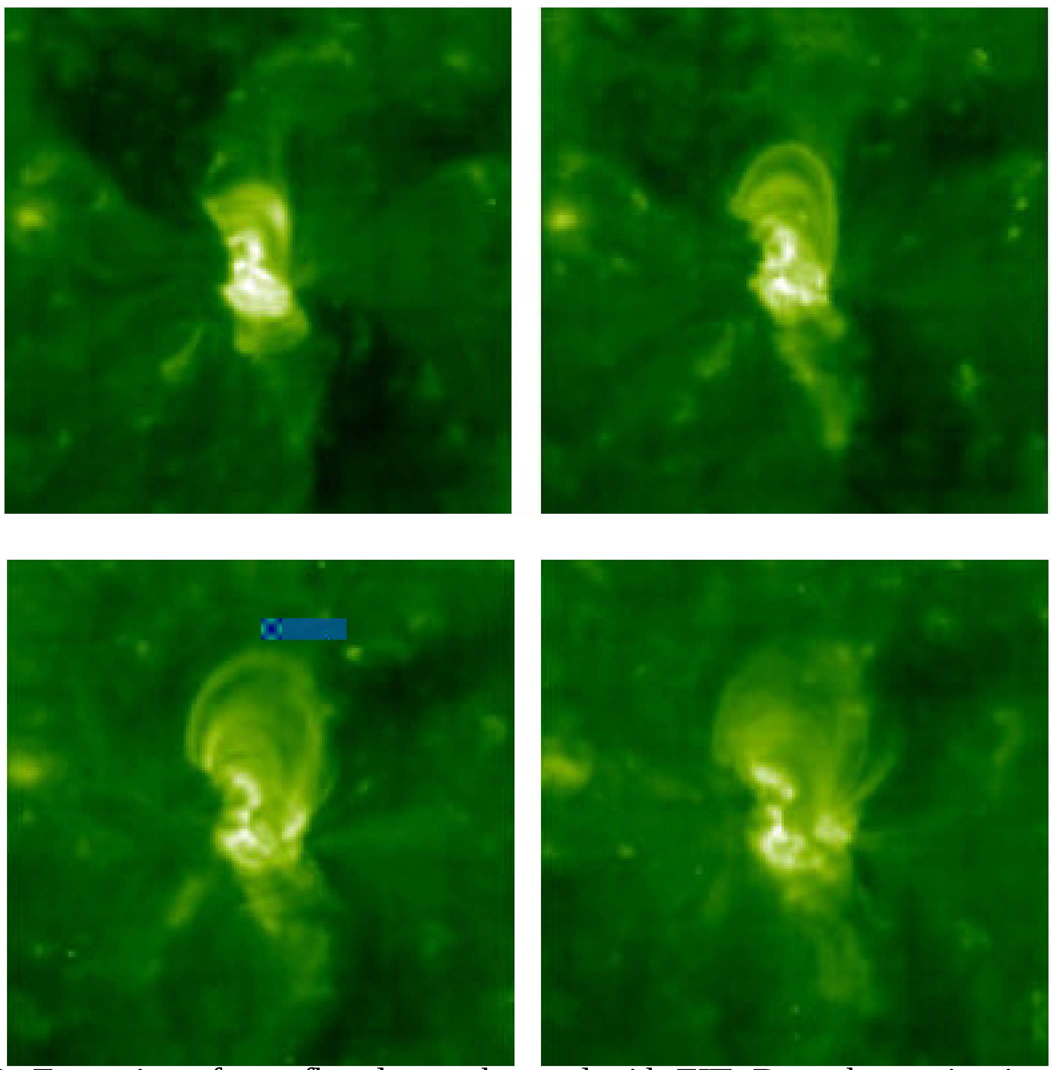


Figure 3: Expansion of post-flare loops observed with EIT: Does the motion in the image plane correspond to genuine mass motion, or to successive illumination of nested loops? Imaging alone cannot discern the difference, while time/space resolved spectroscopy can measure directly the motion of the loops.

High Time Cadence Imaging Spectroscopy

A high resolution imaging spectroscopy mission, such as the proposed ESSEX mission, will record spectra on time scales as brief as 1 second, which is comparable to the mean particle collision time in the lower corona.

By recording spectra of reconnecting structures on temporal and spatial scales that are appropriate to the dynamics of the reconnection, ESSEX will give us the tools that we need to understand the form and quantity of energy released by reconnections on many scales in the corona and chromosphere. In addition to intensity fluctuations and morphological changes, we will be able to identify bulk flows, waves, heating, cooling, particle acceleration, and non-LTE velocity distributions where and when they occur.

These questions are critical to understanding the science of the "Living with a Star" theme, and the flow of energy from our star, through the geospace environment, to Earth.

ESSEX:
A High Resolution, Imaging Spectroscopy Mission

A high resolution, imaging spectroscopy mission that would fill this need is the EUV Solar Spectroscopic Explorer (ESSEX). The ESSEX scientific instrument package consists of a high resolution, vacuum ultraviolet imaging spectrometer with an ultraviolet (C IV formed at 10^5 K) slit jaw camera and two EUV (He II formed at $3x10^4$ K, and Fe XII formed at $1.5x10^6$ K) multilayer telescopes. All four ESSEX detectors can be read out simultaneously with a cadence of one second. This will allow, for the first time, the full spectral determination of bulk motion, wave propagation, and thermal variations at high spatial and temporal resolution in the solar atmosphere.

These combined spectral and imaging data will finally permit a detailed understanding of the processes that carry energy from the convective motions in the photosphere to heat the corona.

TABLE 1. ESSEX Design Characteristics

Instrument Parameter	**EUV Imaging Spectrometer**	**EUV Telescopes**
Type	Single element off-axis parabola, telescope, Wadsworth spectrometer	Ritchey-Chrétien
Aperture	260 cm^2	75 cm^2
F-Number	45	56
Field-of-View (scan range)	± 4.0 arcmin (both axes)	8.5 x 8.5 $arcmin^2$
Wavelength Range	1000-1600 Å (1^{st} order) 500-800 Å (2^{nd} order)	195 Å, 304 Å, 1548 Å
Instantaneous Wavelength Coverage	95.6 Å passband (1^{st} order) 47.8 Å passband (2^{nd} order)	195 Å, 304 Å, 1548 Å*
Entrance Slit Size	0.33 x 100 $arcsec^2$; 1.0 x 100 $arcsec^2$	N/A
Detector	Intensified CCD	backside-thinned CCD
Pixel Format (active pixels)	2048 x 1024	1024 x 1024
Spatial Scale	0.35 arcsec $pixel^{-1}$	0.5 arcsec $pixel^{-1}$
Spectral Scale	23.3 mÅ/pixel (2^{nd} order) at 700 Å	N/A
Spectral Resolving Power	~30,000	N/A
Velocity Scale	~1 km/s at 700 Å	N/A
Dynamic Range	> 10^8	~10^7

* 1548 Å slit jaw camera in the EUV spectrometer.

Comments	λ Range	Ion	λ (Å)	Log T (K)	Spectrometer Count Rate* (counts/s/arcsec²)		
					Quiet Sun	Active Region	Flare
Flare Studies	555-595 Å (2^{nd} order) & 1110-1190 Å (1^{st} order)	O I	1152.1	3.7	40	186	
		He I	584.3	4.2	91	1,084	
		C III	1175.7	4.9	200	928	4,780
		Ne VI	562.8	5.6		44	364
		Fe XIX	592.1	6.8			3,750
		Fe XX	567.7	6.9			2,440
		Fe XXI	585.8	7.0			1,270
Line Ratio diagnostics	674-722 Å (2^{nd} order) & 1348-1443 Å (1^{st} order)	S I	1433.3	3.7	30	97	332,000
		Si IV	1393.7	4.8	477	2,180	166,000
		Si IV	1402.8	4.8	238	1,080	30,090
		O IV	1401.1	5.2	65	413	
		Mg IX	706.1	5.7		60	720
		Fe XII	1349.4	6.2		100	1,450
		Fw XX	721.4	6.9	0.3	1.2	20,500
Broad Temperature range (dynamic studies)	750-790 Å (2^{nd} order) & 1500-1580 Å (1^{st} order)	S II	1526.7	4.1	57	286	
		N III	764.3	4.9	8.5	41	5,790
		C IV	1548.2	5.0	510	2,790	362,000
		N IV	765.1	5.2	75	417	26,900
		O V	760.2	5.4	26	215	13,700
		Ne VIII	770.4	5.8	56	890	3,660
		Fe XIII	786.1	7.0			2,160
EUV Imagers	304 Å	He II	304	4.5	800	1,000	-
	1550 Å	C IV	1550	5.0	1400	2,800	364,000
	195 Å	Fe XII	195	6.2	32	400	380,000

Table A-2. Temperature coverage and estimated count rates of selected emission lines in single detector wavelength window of ESSEX spectrometer and EUV imagers.

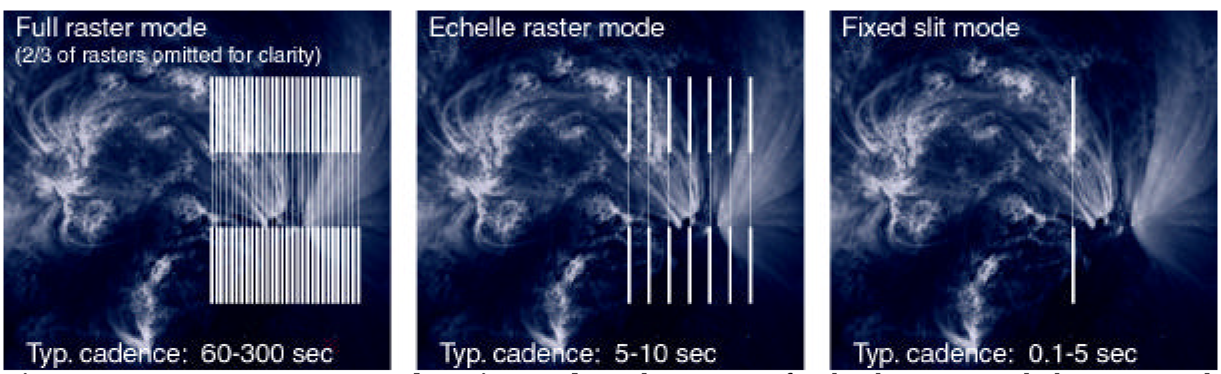
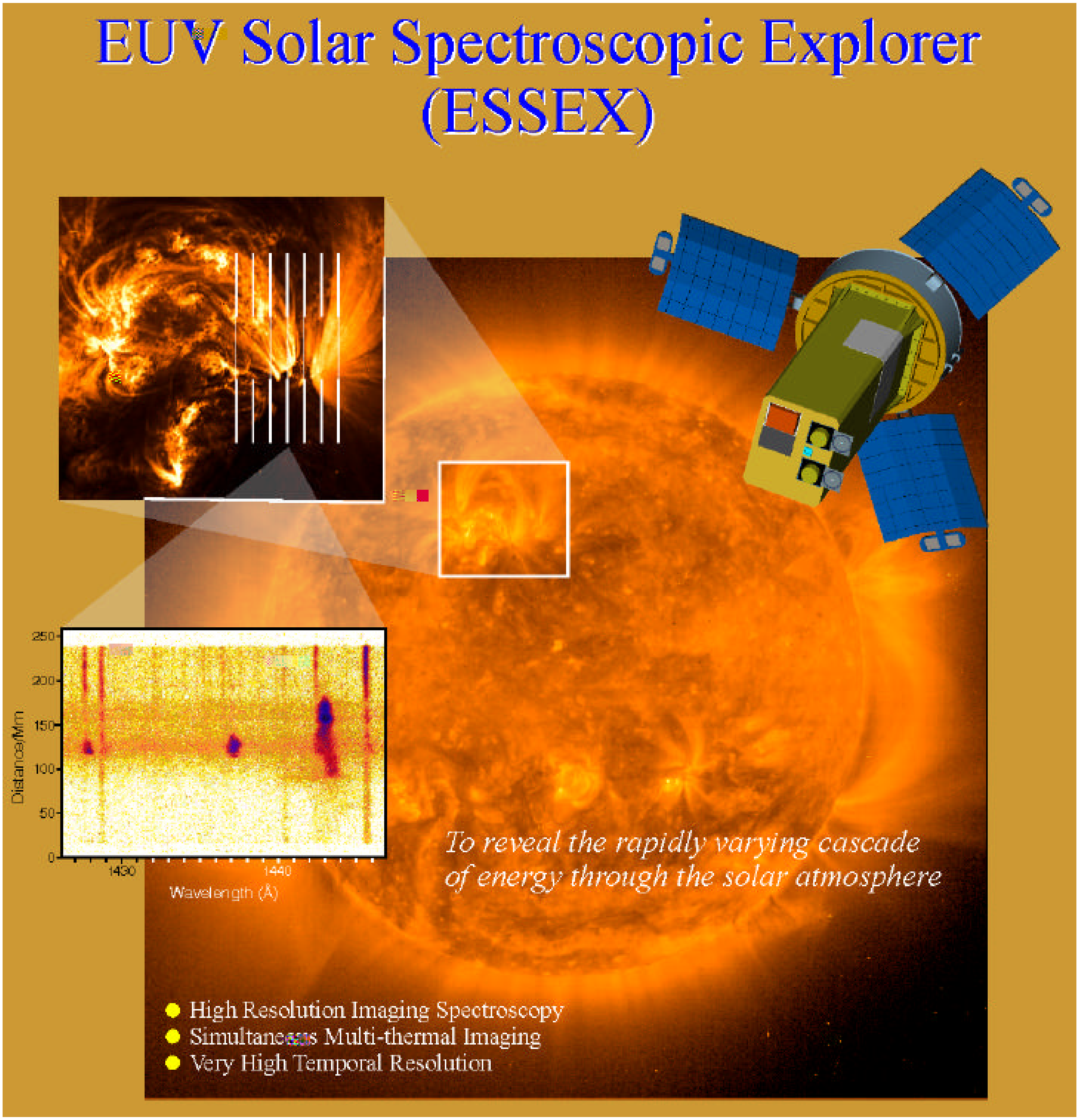


Figure 4: ESSEX Spectrometer Observing modes. Slit positions for the three principal observing modes are depicted, to scale, on a TRACE 171Å 200x200 arcsec^2 image showing coronal "moss" under an active region. Cadences are given for typical line selections and exposure times for each mode. Slit exposure times are typically 1-2 seconds for bright lines (used in the echelle scan); 1-5 seconds for a broader line selection (in the full scan). ESSEX can expose and read out the very brightest lines – Ly α 1216Å and C IV 1548Å – in under 100 milliseconds.


EUV Solar Spectroscopic Explorer
(ESSEX)
250
200
150
100
50
0
Distance/Mm
1430
1440
Wavelength (Å)
To reveal the rapidly varying cascade
of energy through the solar atmosphere
High Resolution Imaging Spectroscopy
Simultaneous Multi-thermal Imaging
Very High Temporal Resolution